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The Space Science Board undertook this study of solar physics at the request of the National Aeronautics and Space Administration (NASA) to help guide the agency's future program. Specifically, we were asked to address the following questions:

- What is the scientific content of solar physics?
- What should be the future scientific directions?
- What should be the appropriate role of NASA in solar physics?

We structured the study in the same fashion as the previous one on space plasma physics (Space Plasma Physics: The Study of Solar-System Plasmas, National Academy of Sciences, Washington, D.C., 1978). We created a Study Panel, composed of members with broad scientific interests, and an Advocacy Panel, composed of practicing solar physicists and scientists with related interests.* The purpose of this structure was to obtain an impartial assessment of the scientific content of the field, to identify the critical issues of solar physics, and to mobilize its practitioners to develop plans for future investigations.

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The Physics of the Sun

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and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PART I. SPACE SCIENCE BOARD OVERVIEW

The Space Science Board undertook this study of solar physics at the request of the National Aeronautics and Space Administration (NASA) to help guide the agency's future program. Specifically, we were asked to address the following questions:

o What is the scientific content of solar physics?

o What should be the future scientific directions?

o What should be the appropriate role of NASA in solar physics?

We structured the study in the same fashion as the previous one on space plasma physics (Space Plasma Physics: The Study of Solar-System Plasmas, National Academy of Sciences, Washington, D.C., 1978). We created a Study Panel, composed of members with broad scientific interests, and an Advocacy Panel, composed of practicing solar physicists and scientists with related interests.* The purpose of this structure was to obtain an impartial assessment of the scientific content of the field, to identify the critical issues of solar physics, and to mobilize its practitioners to develop plans for future investigations.

The earlier space plasma physics study stressed the important connections between plasma and solar physics, resulting in a closer relationship of these areas of research. In a similar manner, the current Study Panel stresses

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* The Advocacy Panel was organized in several parts: an Advocacy Scientific Panel responsible for preparing a number of detailed review papers covering all areas of solar physics; an Advocacy Policy Panel formed to address the questions of future research directions and NASA's role; and an Advocacy Committee to manage the advocacy part of the study, summarize the work of the two panels, and frame recommendations.

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the important relationships of solar physics to astrophysics and physics, establishing the relevance of solar studies to these other areas. In doing so, the Study Panel considers both ground-based and space-based observations, thereby providing a broad context for those solar observations best accomplished from space. As noted by the Study Panel, both it and the Advocacy Panel reached similar conclusions concerning the scientific content of solar physics, both as a subject and in relationship to the areas noted above.

As part of this study, the Advocacy Panel evaluated significant recent advances in all aspects of solar physics and recommended seven specific outstanding problems that should be addressed by a vigorous NASA solar research program. The Study Panel report concurs in these recommendations.

PART II. REPORT OF THE STUDY PANEL

1. CONCLUSIONS AND RECOMMENDATIONS

PRINCIPAL CONCLUSIONS

1. The Sun is the most studied of all astronomical objects, other than the Earth. Understanding the Sun's physics is a cornerstone of astrophysics. Detailed understanding of the Sun's complex, variable behavior is a prerequisite for very practical predictions concerning the Earth's environment, including the biosphere.

2. Observations of the Sun from space will continue to be a major element of space research. Because of the Sun's proximity and the resulting challenge to physical understanding, the value of this research is most likely to be judged by its relationship to fundamental understanding.

3. Solar physics once dominated astrophysics, but with the revolutionary advances in galactic astronomy and cosmology of the past half century, solar physics appeared less dominant. With the advances in our understanding of the general physics of other stars, solar physics became partially isolated from the rest of astrophysics, to the detriment of both. The remarkable advances in the power of space observations, however, as well as the advances in solar neutrino astronomy and solar seismology of the past quarter century have once again brought solar physics to the forefront. We believe that solar physics continues to have major value because its problems and questions directly contribute to physics and to astrophysics in general. We are enthusiastic about the new fundamental questions of physics and astrophysics emerging from solar observations, and we are strongly encouraged by the present awareness of the interdependence of solar physics, physics, and astrophysics.

PRINCIPAL RECOMMENDATIONS

1. In order to advance our understanding of the physics of the Sun, a substantial observational program is required. In the selection of these programs attention must be paid to basic scientific problems and to the logical sequence of theoretical problem definition, the planning of experiments and missions, data collection, data reduction, and theoretical analysis, which lead to progressively refined understanding.

2. We perceive a special need to encourage and support the university role in solar physics. This role is strongest when theory and experiment are close and when faculty and students share discovery.

3. The strength and support of solar physics among scientists depend on the degree to which its scientists pursue challenging physics and astrophysics questions. The recognition and support of individuals who identify and help to solve such problems is crucial to the scientific strength of the field. Further desirable interaction of solar physics and astrophysics is a natural consequence.

4. We believe that the current balance between theory and experiment in solar research is appropriate. We also find that because solar physics is currently observation limited, more numerous space observations will be required. Ground observations will play a complementary role. Numerical modeling has made, and will continue to make, a major addition to solar understanding.

2. INTRODUCTION

The ultimate astrophysical challenge is the comprehension of the universe. From the physics of particles and fields we perceive the fundamental laws of nature. Our ability to apply these laws, learned in the laboratory, throughout the universe depends on the interpretation of what we observe. Even the most baffling laboratory experiments are likely to be understood eventually because they are accessible; but nature has devised highly complex and inaccessible experiments--what we call stars and galaxies and their associations. The outstanding member of this class is the Sun--outstanding, because it is so important to our existence. It is also unique because of its proximity and consequently challenges our ability to observe and understand. Otherwise, it is a very ordinary star--unglamorous because of its seemingly benign constancy. This relative constancy has afforded the eons necessary for the development of life.

The Sun, as a physical laboratory, is the one observationally accesible object that requires a synthesis of the four principal forces of nature (gravitational, electromagnetic, nuclear, and weak) to arrive at a unified description using quantum mechanics, statistical mechanics, fluid dynamics, and magnetohydrodynamics. Nothwithstanding the historical success of this enterprise, the Sun still eludes our full understanding; that is, we are not able to use the known laws of physics to construct a consistent model for important observations (see Chapter 7).

It has become clear that the "external Sun" is a complicated, unsteady generator of light, radiation, and particles. Every aspect of the Sun has become surprising on careful examination. Physics is challenged by the solar behavior, both external and internal and both short term and long term. The puzzles concern fundamental questions such as the properties of elementary particles, the hydrodynamics of global circulation, the generation and anomalous dissipation of the magnetic fields that produce the perpetual and extreme non-local thermodynamic equilibrium (non-LTE) surface variations called "activity." Recent observations have now established that general surface activity is likely to occur on all classes of stars. The physics of the Sun is one of the major scientific challenges of the last decades of the twentieth century, with immediate implications for the physics of stars in general, and for the physics of the terrestrial atmosphere in particular.

The physics of the Sun has come through an extraordinary period of exploration and discovery, beginning with the ground-based spectral studies of the first nalf of the century and enormously expanded by the ground-based and space observations of the second half. The central questions of the Sun can be addressed only with the support of the wide range of precision observations frequently possible only from spacecraft, unencumbered by the obscuration of the terrestrial atmosphere.

Among the crucial observations that may be best performed from space are the studies of the gravitational moments, the long-period oscillations, the variations in luminosity, the gigantic eruptions into space, the outward extension of the active regions, the quantitative study of the very fine structures (less than 100 km) at the heart of so much of the activity at the visible surface, and the observation of the remarkably complex transitions of the solar atmosphere from the visible surface at 6000 K to the 2×10^6 K of the corona and then to the solar wind.

A solid theoretical understanding has begun to develop, and the field is entering into the "hard science" phase, with observation, theory, and numerical experiments developing in close coordination with each other, and more recently coordinated with the physics of stellar activity, with solar terrestrial physics, with the physics of the heliosphere, and with laboratory plasma physics.

As scientists, we view the search for this complete understanding as the most valuable aspect of the science of the Sun. We will describe some current problems of solar science that lack firm theoretical understanding; but first, we review the broader motivations for solar research.

3. MOTIVATIONS FOR RESEARCH

The scientific study of the Sun has the following three motivations:

1. As exploration--to satisfy human curiosity about the universe.
2. For its intellectual significance, as a test of our ability to use the laws of physics to reach comprehensive understanding of one, and from this one, many stars.
3. For its practical importance--in order to understand the Earth's environment and to predict its future changes.

We are passing through a new exploratory phase of solar research made possible by both space experiments and ground-based observations. Nevertheless, it is our unanimous opinion that the strongest justification for solar research is based on scientific problems whose solutions are sought in light of the most advanced knowledge of physics and astrophysics.

On the practical side, the climate and environment of the Earth is sensitive to small variations in the solar radiation flux, and possibly also the solar plasma and energetic particle output. It is important, therefore, that these variations be understood to the point where they can be predicted. A firm commitment to theoretical development is essential for our ability to predict.

4. HISTORICAL ACHIEVEMENTS OF SOLAR ASTROPHYSICS

Historically, the Sun provided the primary motivation for modern astrophysics. The Sun is the local stellar laboratory, where the structure and activity of a typical middle-age, main-sequence star can be studied in detail. The disk of no other star can be so well resolved.

It was the Sun that yielded the first measurement of stellar mass, in the late eighteenth century, from the laboratory measurement of Newton's constant of gravitation. In the nineteenth century it was the Sun that presented the evidence leading to the conclusion that a star is a self-gravitating ball of gas. It was the Sun that first provided helium for the spectroscopist and exhibited the chromosphere and corona during eclipses to challenge and baffle the physicist. It was the need to reconcile the energy of the Sun with the age of the solar system that prompted the understanding of thermonuclear reactions and the nuclear synthesis of the elements.

The first stellar magnetic fields were detected in the spots on the Sun, and sunspots and the associated flares were the first evidence of stellar activity. Studies of the ionized state of matter in the Sun led to the emergence of plasma physics. Indeed, the characteristics of the solar corona and solar activity are so remarkable and so contrary to expectations (even today) that their nature could be conceived of only because they were thrust before our eyes by the Sun. It has been possible to relate the concepts of coronal expansion to stellar winds only because direct observations of coronal conditions near the Sun and of wind conditions in interplanetary space compelled us to the idea.

The entire subject of non-local thermodynamic equilibrium (non-LTE) radiative transfer in stellar atmospheres was constructed on the detailed evidence from the Sun, without which the subject would have been stagnant for decades. Once non-LTE theory was established, it could be confidently extended to other stars.

More recently, detailed studies of the ultraviolet and x-ray emission from the filament and loop structures in the transition region and corona of the Sun have begun to define what makes an active corona. We believe that most other stars have active coronas, but there has been no way to determine the cause of the phenomenon. And even with the Sun, the understanding of the corona must be developed further before it can be considered adequate.

The nonuniform rotation of stars can be studied directly only for the case of the Sun, where the problem now appears to be more complicated than had been imagined. The internal oscillations of a star can be clearly observed only in the Sun.

The general filamentary structure of the stellar magnetic field was discovered only because of the proximity of the Sun. Small magnetic knots and sunspots are the most obvious manifestation of this remarkable effect, which is still not understood despite the detailed information available.

5. THE FUTURE OF THE SCIENCE OF THE SUN

The potential for the intellectual growth of any field of science depends in part on the perceived universality of the solutions of its unsolved problems. The Sun is no exception. The universality of the unsolved physics problems of the Sun then becomes our strongest affirmation of the validity of the science of the Sun. All research of the Sun, and especially research from space, attains validity by association with these problems. Our purpose is to review those problems of solar research whose significance extends to physics and astrophysics in general. We believe that this provides the context for those aspects of scientific questions that can be addressed from space. Hence we emphasize four general, abstract problems of the Sun, vital to the further understanding of the Sun as well as of the stars.

We do not imply relative importance by the particular order in which we present these problems; only that they represent fundamental problems of broad application to all of astrophysics:

A. The Sun is the single best-observed working dynamo.* Some manifestations of the magnetic fields of dynamo action are the solar magnetic activity, coronal structure, and wind. The problem is, how does a dynamo work?

B. The Sun has a convective envelope that affords a unique opportunity to observe its behavior and deduce therefrom a fundamental understanding of turbulent heat transport in a gravitional field. This understanding can then be compared to the behavior of other stars as well as the Earth's atmosphere. An explanation of these observations requires fundamental innovations in the physics of turbulence and turbulence in the presence of magnetic fields and ionization. How does convection work in detail?

C. Turbulent convective motions and magnetic fields are intimately related. The manifestation

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* The Earth's dynamo is closer but its workings are relatively obscured by the Earth's mantle and the slow time scale of the motions of the core.

of this interaction at the solar surface leads to non-local thermodynamic equlibrium (non-LTE) phenomena so exotic--known as solar activity--that the plasma physics and magnetohydrodynamics become problems in themselves. What is the physics of solar activity?

D. The internal structure of the Sun is a challenge to astrophysics. The structure is inferred from theory, normal-mode analysis, neutrino flux, and gravitational shape. Does the theoretical structure agree 'ith measurements?

The selection of these problems is not unique. For example, the Space Science Board report on Space Plasma Physics: The Study of Solar-System Plasmas (National Academy of Sciences, Washington, D.C., 1978), emphasized that magnetic reconnection and particle acceleration were not yet understood and have a strong bearing on solar surface activity as well as on all of plasma physics. Similarly, the processes that regulate radiation transport in the solar atmosphere are important to radiation physics and stellar atmospheres.

We discuss four problems, but single out the internal structure for greatest emphasis because it is the simplest example that illustrates the scientific breadth and astrophysical relevance of the problems of the Sun. This example is a strong affirmation of the quality of solar research. The affirmation of scientific quality of solar research is the primary conclusion of this report. It may be that the problem of the solar dynamo is the toughest to solve, or that the problem of turbulence in the envelope has the greatest relevance to both science and terrestrial problems, or that the interaction of turbulence and magnetic fields is the most difficult. It may be that problems not yet considered here hold the long-term future of solar physics.

A. INTERNAL STRUCTURE OF THE SUN

Current knowledge of the internal structure of the Sun is almost entirely based on theoretical models. Since the matter in the solar interior is nearly a perfect gas we expect model calculations to be very accurate.

The astronomically determined input parameters original composition is inferred from spectroscopic studies of the solar atmosphere and from the composition of the solar wind and meteorites; the age is taken to be that of the oldest meteorites. Laboratory experiments, together with quantum-mechanical calculation, provide the relevant atomic- and nuclear-physics parameters. The lack of a fundamental theory of turbulent convection forces us to add one ad hoc parameter--the mixing length. This input determines a model for the interior of the present-day Sun that is virtually uniquely determined, except for the depth of the outer convection zone.

It would be valuable to have observational tests of the model. Measurements of neutrino fluxes, the shapes or departures from sphericity of the photosphere and the external potential surfaces, and the frequencies of the free oscillations are beginning to provide such tests. We next discuss these manifestations of structure in greater detail.

The Solar Neutrino Experiments

The first solar neutrino experiment, using a ^{37}Cl detector in a deep mine, has been running for over 10 years and has produced only a single number, the mean counting rate. The fact that the measured rate is appreciably smaller than the theoretical prediction is having a profound effect on astrophysics in two very different directions. First, it raises a bold challenge to some of the most basic tenets of astrophysics or particle physics. Do some unsuspected modes of oscillation convert the Sun into a variable star? Do neutrinos have finite masses? If so, would neutrino oscillations during the flight from the Sun to the Earth decrease the detectable fraction of neutrinos? Second, it is leading to a painstaking refinement of techniques in a multitude of auxiliary fields--opacity calculations, nuclear cross-section measurements, stellar evolution computations, and cosmic-ray events. The exciting though inexact science of astrophysics will mature by having to solve one problem from beginning to end without shortcuts.

The importance of quantitative detail in uncontroversial theories is peculiar to the chlorine detector, whose counting rate depends sensitively on the exact temperature profile of the solar interior. Proposed future experiments, especially one using ^{71}Ga as a detector, are much less sensitive to these details and should provide a crucial test: If the ^{71}Ga experiment is in agreement with theoretical predictions, only the details need improving. If it also gives a rate lower than expected, some of our basic concepts are wrong. In the later case, a third experiment might tell us which concept is wrong.

The Shape of the Sun and Its Potential Surfaces

An idealized Sun in static pressure equilbrium must be precisely spherical. Measurements of departures from spherical symmetry provide information not otherwise obtainable about the solar interior.

The science of physical geodesy has yielded useful information concerning both the mass and stress distribution inside the Earth. The nearly perfect-fluid character of the solar interior makes the interpretation of the solar shape easier than that of the Earth. Fluid viscosity is negligible, and, in addition to the gas pressure, the only significant stress fields are the Maxwell stress of the magnetic field and the Reynolds stress of quasi-stationary fluid flows such as rotation and convection.

Important and interesting questions concerning the structure and origin of the Sun might be answered by knowing its shape. Primordial magnetic fields may be trapped in the solar core, and the core may be rotating faster than the surface.

There are two basic methods for determining the shape of a potential surface: (a) A dedicated zero-drag solar orbiter moving in an orbit of large eccentricity and high inclination could be used to map the solar gravitational field. (b) The optical shape of the Sun could be measured and corrected for the effect of surface fields. Ideally, this last measurement would be carried out from space to avoid the distortion due to the Earth's atmosphere.

Solar Oscillations

The determination of the frequencies of the Sun's normal modes of oscillation would provide us with a sensitive probe of the solar interior. If an appreciable number of low-frequency modes were detected, the basic variables (pressure, density, and temperature) could be deduced with only a little help from theory. Even the internal rotation of the Sun would be subject to observational study through the splitting of the modal frequencies that it produces.

The most productive studies to date have concerned the modes with periods near 5 minutes, collectively known as the 5-minute oscillations. The oscillations have been observed in two domains of global structure--the highly nonradial modes that are confined to the outer part of the Sun and the nearly radial modes that penetrate to the solar center. The precise frequencies of the highly nonradial modes are sensitive to the specific entropy in the convection zone. The observations are best fit by solar models that have convection zones and require a high efficiency for subsurface convection. Although the frequencies for the nearly radial modes are close to the theoretical predictions, they differ by an amount that may be significant.

Future observations should aim at the detection of longer-period modes that probe deeper into the solar interior. These extremely sensitive observations may be done best from space.

B. THE SOLAR DYNAMO

As far as it is known, all of space is pervaded with magnetic fields. Unless the early universe contained a significant fraction of monopoles, however, the big bang had to have been magnetic-field free because the expansion would have led to a large anisotropy. Because the present free-monopole density is limited by galactic-field annihilation, it is universally believed that all magnetic fields in the universe are the result of dynamo action. An astrophysical dynamo is a flux generator in a conducting fluid driven by hydrodynamic motions. We are closest to the dynamo of the Earth, but we can "see" the effects of the dynamo of the Sun in greater detail because the Sun's region of high electrical conductivity extends to the surface.

The fluid deformations that can lead to magnetic-flux generation--the α effect--are well understood conceptually. Indeed, the necessary periodic helical and radial translations are an expected result of convection in rotating, self-gravitating systems. Nevertheless, it is not proven that this is the actual mechanism of flux generation in the Sun or other stars. The behavior of magnetic flux, particularly its diffusion and annihilation (reconnection) in a conducting turbulent fluid, is not universally agreed on. At some point in a dynamo, reconnection of flux must occur. Where this occurs in the solar or in stellar dynamos is unclear. The galactic dynamo is still more problematic, although probably following from the same basic principles.

Dynamo theory remains a central challenge to the subject of continuum magnetohydrodynamics. The Sun is the most accessible observational manifestation of a working astrophysical dynamo.

C. SOLAR CONVECTION

In the cooler outer layers of the Sun, opacities increase to the point that the radial temperature gradient exceeds the critical value for gravitational fluid instability. Convection therefore takes over as the principal heat transport mechanism in an outer shell, whose thickness is perhaps 20 percent of the solar radius. Theoretical analyses of the thermal properties evident in granulation and supergranulation, angular momentum properties evident in differential rotation, and magnetic-field properties evident in solar activity cycles all depend on an understanding of the properties of the solar convection zone. Convection is buoyancy-forced turbulence, and no satisfactory simple theories exist for either convection or turbulence. Yet, problems of convection and turbulence arise in so many contexts that any progress toward finding satisfactory and computable approximations to solar convection properties will also benefit subjects as diverse as weather prediction and magnetic confinement fusion.

Convection and turbulence are characterized by chaotic fluid motions over a wide range of space and time scales. Owing to the essential nonlinearity of the dynamics, there is no possibility of decomposing the motion into independent modes. We are generally interested in the statistical properties of such systems, such as average heat and momentum transport, although we may also want to predict the detailed evolution of larger and slower scales of motion.

The most complicated manifestation of convection is its interaction with magnetic fields leading to phenomena on a scale smaller than is presumed for the dynamo itself. We are concerned with singularities in the chaos of the turbulent field, both as manifested in magnetic phenomena as well as possible intermittency in the fluid motions.

D. THE SOLAR SURFACE

The surface of the Sun is a highly complex zone where competing transport phenomena interact. The optical surface is by definition the transition region where radiation transport of solar luminosity becomes transparent rather than diffusive. At this same level, departures from local thermodynamic equilibrium also begin to be seen. The complex opacity behavior of solar matter leads to the fairly mature topic of "gray" atmospheres, where a general consensus of understanding now exists. However, it is noteworthy that the last factor-of-100 discrepancy in the observed solar thermal spectrum in the ultraviolet was only understood theoretically in the last few years. The dominant physical processes change rapidly with height above the solar surface, often leading to rapid changes in time and space scales of dominant features in the atmosphere.

Convective Radiative Boundary

The optical surface of the Sun is close to the boundary where convective heat transport is superseded by radiative transport. Below the convective zone of the Sun, the heat flow is also radiative. There is speculation concerning the degree of convective turbulent penetration at this boundary and its consequences for solar and stellar isotopic mixing. At the upper surface penetration by convection also occurs above the level at which buoyancy forces are dissipated by radiation, owing simply to the turbulent momentum of rising fluid elements. It is only through this complex window of turbulence and radiation transport that we are able to make quantitative measurements of the miniscule motions that we interpret as solar oscillations.

Magnetic Pressure, Thermal Pressure, and Turbulent Pressure Boundaries

The solar surface is also close to the level above which magnetic stress dominates over plasma pressure and to another level above which magnetic energy becomes large compared with the turbulent kinetic energy. The result is that above the solar surface magnetic pressures become stronger than either turbulence or plasma pressure and hence only the "feet" of magnetic loops are perturbed by solar surface motions. Below the surface our knowledge is less secure. Contrary to naive expectations, convective turbulence does not immediately disperse the fields, but the opposite occurs: the field seems to be concentrated in small intense filaments.

Evidence of convective motions deeper below the surface, perhaps several thousand kilometers, comes from the supergranulation time scale of changes in a day compared with the smaller structures of granulation that evolve in minutes and are presumed to be within a scale height of the surface (300 km). Evidence for the deepest motions, perhaps to the base of the convective zone at several tens of thousands of kilometers comes from the slow evolution of active regions that take several weeks to form and decay.

Current Limit Boundary

At higher elevations above the optical surface a third boundary is reached where particle densities become low enough to permit both nonequilibrium plasma behavior and significant anisotrophy of current carrier distribution functions. Here there is a natural onset of plasma instabilities, leading to enhanced reconnection and magnetic-field energy conversion that produce the extreme suprathermal effects collectively called solar activity. The activity involves selective acceleration of particles, into the relativistic range on special occasions, and a general heating of the gases to 10^5-10^8 K, causing intense variable emission of EUV, x rays, and gamma rays. Laboratory simulations of this phenomenon have required the mapping and theoretical interpretation of the multidimensional spaces of time-dependent magnetic-field and particle distribution functions. It is likely that the extreme reconnection phenomenon of solar flares will require just such a complicated analysis.

The most dramatic confrontation of theory and observations of the surface still remains the remarkable energy conversion of solar (and stellar) flares. Here it is generally believed that a significant fraction of the energy of the magnetic field, thousands of kilometers in dimension, is converted to energetic particles in several seconds. The implied resistivity, filamentation, wave excitation, or whatever, defies current plasma theories. The reconnection of the rapid "disruption instability" of tokamak or reverse-field-pinch fusion reactors is analogous, but the comparison so far is inadequate to explain a flare. The surface of the Sun represents a major challenge to cur ability to model and understand.

6. PRACTICAL IMPLICATIONS OF THE PHYSICS OF THE SUN

The steady component of solar radiation sustains life on Earth, but the practical implications of th observed solar variabiity are not always so clear.

The bulk of the radiation from the Sun is remarkably steady. Climate model studies suggest that a 1 percent increase in solar radiation incident on the Earth would increase the mean surface temperature of the Earth by about $2^{\circ}C$. The heat capacity of the oceans would, however, delay the response by several decades. Recent measurements from spacecraft reveal changes in total solar flux of a few tenths of 1 percent over a few days. Changes over decades are believed to be less than 1 percent but it is clearly important to determine more precisely what they may be.

The ultraviolet end of the solar spectrum, although constituting only a small fraction of the total, is more variable with fluctuations of order 10 percent. Such fluctuations influence directly the stratospheric ozone balance and thermal structure and might indirectly influence the tropospheric climate through possible wave-trapping effects.

The adverse impact of solar magnetic disturbances on telecommunications is well known and has led to efforts to forecast them as reliably as possible. High-energy particle-emitting events with absorption in the Earth's upper atmosphere also have a well-recognized impact, particularly at high latitudes, on atmospheric chemistry and electricity and on man's safety in space.

Much more controversial has been the impact of solar variability on weather and climate. Many statistical studies have sought correlations between climate and solar activity cycles, but these have, at best, been so weak that they have little practical value for prediction.

The climate system has a large sampling-noise component coming from unpredictable weather fluctuations, and this requires long averaging times to detect the effects expectd from solar variability. For this reason, a search for physical linking mechanisms may be more fruitful.

7. THE CONDUCT OF SOLAR SCIENCE

A scientific subject endures only because of a consensus as to its intrinsic worth. This value judgment concerns both the topics as well as the capability of its practioners. We have strongly endorsed the intrinsic scientific value of the science of the Sun. It is now imperative to encourage the best scientific endeavor.

QUALITY AND THE PROPOSAL VERSUS THE REVIEW PROCESS

Quality in science depends on the intelligence, integrity, dedication, education, and support of its practitioners. Their education and support depend significantly on the relationships between funding agencies, the scientific communities, and the individual scientist. Since research directions are influenced by the selection of the research to be supported, the improvement of the quality of solar science will require continuing dedication to the quality of the review process. Facility-type instrumentation, where successful proposals lead to partially dedicated access by the proposing group to instruments, is one successful way to improve both proposals and reviews. Opportunities for observations should be actively publicized outside the solar-physics community, as well as within it.

RECOGNITION OF THE PAST

Increasingly detailed and comprehensive studies of the Sun have been carried out over the past several centuries, and present solar research is necessarily more specialized than that on any astronomical object other than Earth. This specialization had two effects: solar scientists were not challenged and stimulated frequently enough in the wider scientific arena of physics and astrophysics where interaction and competition would steadily refine ideas and techniques; the general astrophysics community made less use than it should have of the refined experimental techniques and theoretical conceptions that have been brought to bear on solar science. We see that currently there is recognition of these problems and that there has been rapid progress toward their solution.

WIDER REPRESENTATION

This panel believes that one way to strengthen the interaction between physics, astrophysics, and solar science is through the peer review process. We recommend that panels, advisory boards, and project definition teams concerned with solar research and astrophysics have mutual representation both to encourage selection of research because of its solar and astrophysical significance, as well as to propagate more widely the respective theoretical achievements and experimental techniques. In addition, publications and conferences should reach both audiences as widely as feasible.

UNIVERSITY SUPPORT

The future of solar physics depends on the number, quality, and training of its students. This training requires research opportunities. Since mission planning, execution, and data reduction cover for space research so long a time span, students must enter the research and discovery process early. As a consequence, university support in space research requires special commitments. In addition, we agree with the Advocacy Panel that solar physics, as a university subject, is most meaningful as a specialization following a fundamental education in physics.

8. PROGRESS IN THE FIELD

Both before and since this study was initiated, there has been rapid progress in the improvement of the field of solar science. The primary reason for this improvement is that the new developments in understanding the physics of the Sun in the past decade have been so significant that it has initiated the revitalization of solar physics. In addition, the commonality of some observations and techniques with other astrophysical observations has encouraged an integration of the fields. Continuation of this progress depends on new observations and the unsuspected discoveries to which they lead.

We believe the report of the Advocacy Panel represents fairly the best of solar research, and we wholeheartedly support its recommendations.

We recognize that the recommendations of the Advocacy Panel must also be concerned with immediacy of research because what one wants to do depends most often on what can be observed. We, therefore, believe that the advocacy recommendations are consistent with both fundamental physics problems and the practical limitations of measurement. Most importantly the Advocacy Panel has reached similar conclusions concerning the intellectual content of the subject of solar physics.

PART III. REPORT OF THE ADVOCACY PANEL

PREFACE

As part of the procedure of setting up an Advocacy Panel for this study, the Committee on Solar and Space Physics of the National Research Council's Space Science Board invited Thomas Holzer, Dimitri Mihalas, Roger Ulrich, and myself to serve as an Advocacy Committee. We briefly considered the possibility of following the example of the previous study on Space Plasma Physics in setting up three or four separate panels covering different areas of solar physics. However, on close inspection, we found that such a division would be artificial and counterproductive. It did however prove fruitful to divide the panel in another way.

The questions to be addressed by the Study Panel and Advocacy Panel were:

o What is the scientific content of solar physics?

o What should be the future scientific directions?

o What should be the appropriate role of NASA in solar physics?

We decided to organize one panel, called the Advocacy Scientific Panel, to address the first question and another panel, called the Advocacy Policy Panel, to address the second and third questions.

The task of the Advocacy Scientific Panel was to prepare a number of detailed reports covering all areas of solar physics. We were fortunate to be able to recruit the following distinguished panel of scientists with expertise not only in solar physics but also in nuclear physics, atomic physics, and spectroscopy; plasma physics and magnetohydrodynamics; solar-terrestrial rexations; and more general areas of astrophysics: R. G. Athay, J. P. Boris, T. M. Brown, J. Cassinelli, N. U. Crooker, R. E. Dickinson, M. A. Forman, P. A. Gilman, M. Goldman, W. Huebner, W. M. Kaula, B. C. Low, K. B. MacGregor, J. T. Mariska, B. W. Mihalas, M. Newman, R. W. Noyes, F. Q. Orrall, P. Parker, C. W. Pneuman, W. Press, R. Ramaty, G. C. Reid, E. Rhodes, R. Rosner, G. L. Siscoe, D. F. Smith, D. S. Spicer, R. K. Ulrich, and E. G. Zweibel.

These reports, together with a summary prepared by the Advocacy Committee, are now being published as a monograph: Physics of the Sun, editors P. A. Sturrock, T. E. Holzer, D. M. Mihalas, and R. K. Ulrich (Reidel, Amsterdam, Holland, 1985).

In responding to the second and third questions above, the Committee relied for advice on the Advocacy Policy Panel composed of the following distinguished solar physicists: L. W. Acton, R. C. Canfield, J. W. Harvey, H. S. Hudson, A. S. Krieger, R. M. MacQueen, R. W. Noyes, A. B. C. Walker, and J. B. Zirker. Since the first meeting of this panel was held in Phoenix, Arizona they were affectionately known as the "Phoenix Group."

In addition to its meetings with the Advocacy Scientific Panel and the Advocacy Policy Panel, our committee had the privilege of meeting with representatives of the Study Panel on three occasions and with the Committee on Space and Solar Research on one occasion. We also acknowledge with gratitude the participation in one of our meetings of Frank Martin, then Director of the Astrophysics Division of NASA.

Our study benefited greatly from the availability of materials kindly provided by J. David Bohlin of the Solar Physics Office at NASA and from the tireless and efficient efforts of our Executive Secretary, Richard C. Hart. The Advocacy Committee, with the support of our panels, formed an overall picture of the scientific content of solar physics, which was consistent in broad outline with that of the Study Panel. It is also notable that these essentially parallel assessments of solar physics, by the Study Panel and by the Advocacy Panel, have arrived at very similar conclusions concerning current critical issues and plans for future investigations.

In preparing their review of the scientific content of solar physics, the Advocacy Scientific Panel benefited greatly from the efforts of a number of scientists who generously agreed to review individual reports. We therefore wish to thank the following individuals for this valuable contribution to the work of the Advocacy Panel: S. K. Antiochos, E. H. Avrett, J. N. Bahcall, C. A. Barnes, G. Bicknell, D. Black, M. L. Blake, P. Bodenheimer, F. H. Busse, R. C. Canfield, T. R. Carson, J. I. Castor, J. Christiensen-Dalsgaarad,

E. C. Chupp, A. N. Cox, L. E. Cram, P. R. Demarque, L. Fisk, W. A. Fowler, D. O. Gough, L. W. Hartmann, J. W. Harvey, R. F. Howard, P. Hoyng, H. S. Hudson, G. J. Hurford, C. F. Kennel, R. A. Kopp, A. Krueger, R. M. Kulsrud, R. B. Larson, H. Leinbach, R. E. Lingenfelter, J. L. Linsky, D. B. Melrose, M. J. Mitchell, A. G. Newkirk, F. W. Perkins, R. Roble, R. T. Rood, R. Rosner, B. F. Rozsynai, S. Schneider, E. C. Shoub, B. Sonnerup, H. Spruit, R. F. Stein, M. Stix, J. Tassoul, G. Van Hoven, G. S. Vaiana, A. H. Vaughan, S. P. Worden, R. A. Wolf, and J. B. Zirker.

It might help the reader to understand some of the material if I point out the dates at which various components of this report were completed. The Recommendations were put in final form in December 1982; The Scientific Advocacy Report in August 1983; the Summary of this report in January 1984; and this Preface in July 1984.

In conclusion, I wish to thank my fellow members of the Advocacy Committee, Thomas Holzer, Dimitri Mihalas, and Roger Ulrich--none of whom is a solar physicist--for their steadfast and good-humored dedication to the cause of solar physics.

Peter A. Sturrock

SUMMARY OF THE REPORT OF
THE ADVOCACY SCIENTIFIC PANEL

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9. INTRODUCTION

It has long been recognized that the Sun plays a key role in the solar system in influencing the interplanetary medium and the atmospheres of planets. The study of solar-terrestrial relations therefore constitutes one of the most important aspects of solar physics. This assessment has been stressed in several recent studies, and we fully support this emphasis.

The significance of plasma physics in the solar atmosphere, and indeed in the entire heliosphere, has recently been stressed in several studies: by the Study Committee and Advocacy Panels responsible for the Space Science Board review of _Space Plasma Physics in 1978_; by the Committee on Space and Solar Physics of the Space Science Board in its report on _Solar-System Space Physics in the 1980's_; and by the Committee on Space and Terrestrial Research of the Geophysics Research Board in its report on _Solar-Terrestrial Research for the 1980's_. As a result, solar physics is now profiting from a closer relationship with the plasma community, and we find that the plasma community is becoming increasingly aware of and interested in plasma problems arising in solar research, a situation that is advantageous to both fields.

In reviewing the material prepared for the Advocacy Report and in other aspects of our studies, we have become convinced that the relationship of solar physics to astrophysics in general, and to stellar physics in particular, deserves similar close attention. We note, as just one example among many, that an understanding of the long-term evolution of the Sun and solar variability can be obtained only partially from solar observations, paleoclimatic studies, and analysis of meteoritic and lunar samples. A thorough understanding requires the use of additional information that could be obtained from observations of a large number of stars similar to the Sun. A carefully chosen set of such observations would permit the development of a statistical picture of the time-history of solar luminosity variations, cycle morphology, and magnetic activity (including spots and flares) over the Sun's entire lifetime. The existence of such information would make possible realistic estimates of the variation of the Sun's radiation, from its early main-sequence phases to the present, and would allow predictions of its future behavior.

NASA's solar missions of the last decade have changed our view of the Sun in many ways. The most visually dramatic changes came from Skylab. The x-ray telescopes gave us new insight into the structure of the corona, showing that magnetic loops are the fundamental structure of active regions and flares and that coronal holes are the source of high-speed solar-wind streams. In addition, the coronograph on Skylab identified coronal transients--huge masses of plasma ejected by flares and erupting prominences that may travel to the Earth's orbit and cause geomagnetic disturbances.

Skylab set the stage for more specialized physical studies by OSO-8, ISEE, and SMM. As a result of these studies, we have learned that the Sun's corona is not heated purely by sound waves and that the magnetic field must play a crucial role in coronal heating. We have learned that the photospheric magnetic field is not distributed smoothly but is concentrated in small tubes of high field strength, with important implications for all magnetic structures and solar activity. Concerning solar flares, we have learned to distinguish between the primary energy release that occurs in the corona and secondary processes in the chromosphere and elsewhere that involve energy exchange by electron beams, ion beams, heat conduction, and x rays. Our earlier concept that ion acceleration occurs at a later stage than electron acceleration has proved to be incorrect, leading to the search for one process or two closely related processes for accelerating both species of particles. More recently, we have learned from SMM data that one of the fundamental constants of solar-terrestrial physics is not a constant: the solar luminosity has been found to vary on a time scale of one day. This new knowledge comes at a time of renewed interest in the relationship between the Sun and the Earth's climate. It also poses new and difficult questions concerning the propagation and storage of energy through the convection zone.

For all of these and for many other reasons, it is clear that NASA's space missions have brought about profound changes in our perception of the Sun, both as a star and as the central engine of the solar-planetary system.

In evaluating all of this new knowledge and the processes by which it was obtained, the Advocacy Committee has been impressed by the extent to which progress in solar physics is dependent on progress in physics in its widest sense and on the recruitment of scientists trained in theoretical and experimental physics into solar research. Nor is this exchange a one-way street: research in solar physics has throughout history produced a sequence of challenging problems for several disciplines of physics. Several such challenges, drawn from contemporary solar research, are presented in detail in the Advocacy Report and are described briefly in this summary.

The above points will be developed in more detail in the remaining sections of this summary. We first discuss the Sun's interior and then proceed to various layers of the Sun's atmosphere and to a discussion of solar activity. We then discuss the relationship of solar physics to other areas of astrophysics, and finally we discuss solar-terrestrial relations. In discussing each topic, we attempt to point out significant recent advances and problems that appear deserving of special attention for future research. We attempt also to point out which types of spacecraft observations would be most fruitful for attacking each of these problems.

10. THE SOLAR INTERIOR

The essential test of a model of the Sun rests on a comparison with the basic macroscopic properties, namely the mass, radius, luminosity, and composition. Until recently, we thought that the relevant physics was well known except for one deficiency--we have no theory of convection valid for application to stellar structure. For this reason, standard models necessarily involve arbitrary parameters such as the ratio of the mixing length to the scale height. We may therefore note that an important outstanding problem facing solar physicists, and indeed astrophysicists in general, is the development of a reliable theory of convection in stellar envelopes. In recent years, however, confidence in our understanding of stellar interiors has been profoundly shaken by the conflict between the actual measurement of the neutrino flux from the Sun with theoretical estimates of this flux. In attempts to resolve this discrepancy, many questions have been analyzed in detail that previously received only cursory examination as discussed in Chapter 2, Thermonuclear Reactions in the Solar Interior by P. D. M. Parker, and in Chapter 17 by M. J. Newman, The Solar Neutrino Problem--Gadfly for Solar Evolution Theory. As Parker comments, "the observation of solar neutrinos is a crucial test of our understanding of the solar interior, and until we can understand the disagreement between the current model predictions and the current experimental results, we are forced to conclude that after 50 years we still have only circumstantial and indirect evidence for thermonuclear reactions in the solar interior."

Physicists and astrophysicists have considered many possible changes in the physical processes involved in producing the solar neutrino flux. It has recently been suggested that the neutrino may have nonzero mass, in which case each electron neutrino emitted from the Sun would cycle through three states, of which only one would be detected, thereby reducing the count rate by a factor of 3. It has also been noted that the plasma in the Sun's deep interior does not satisfy a basic requirement for the applicability of plasma collision theory (that there be many particles per Debye cube): this calls into question the applicability of standard calculations of thermonuclear reaction rates. Another important outstanding question concerns convection in the Sun's interior: if some mechanism such as convective overshoot or rotationally driven circulation were sufficiently effective for the Sun's interior to be thoroughly mixed, it might be possible to reconcile calculations of the neutrino flux with the data. It must also be stressed that, since Davis' current experiment is sensitive only to the high-energy tail of the solar-neutrino spectrum, there is a strong case for developing detectors, such as the proposed gallium detector, that are capable of measuring the bulk of the neutrino flux.

One of the important unknowns concerning the Sun's interior is its state of rotation. Dicke, in particular, drew attention to this problem and carried out a series of observations on the figure of the Sun from which he was able to extract information relevant to the Sun's internal rotation. The question is still unresolved, and there is no doubt that valuable data, which could perhaps resolve the issue, can be obtained by means of an accurately tracked spacecraft that makes a close encounter with the Sun or by means of accurate measurements of solar oscillations, over a period of years, such as can be made only from space.

Calculation of the neutrino flux depends sensitively on estimates of the internal temperature of the Sun. As W. F. Huebner states in Chapter 3 devoted to Atomic and Radiative Processes in the Solar Interior, "the relationship between pressure, density, temperature, and internal energy of the plasma is determined by the equation of state [but] the relationship of these quantities to the radial distance in the Sun is determined primarily by the opacity." Hence, directly or indirectly, experimental data on the Sun's neutrino flux has stimulated a careful re-examination of atomic and radiative processes in stellar interiors.

Quite recently, a powerful new tool for

examining the interior of the Sun has become available to solar astronomers. This is the study of waves and oscillations visible on the surface of the Sun, a topic that is reviewed by T. Brown, B. Mihalas, and E. Rhodes in Chapter 7, Waves and Oscillations. Since the modal character of the "five-minute" oscillations was first established by Deubner, increasingly accurate and sophisticated measurements have been made, including data spanning several days obtained at the South Pole. As discussed by Brown, Mihalas, and Rhodes, analysis of waves and oscillations will not only help select among prospective models of the Sun's internal density and temperature but also provide information about the Sun's internal rotation. Observations made at the South Pole, with a time base of over a month, already indicate that the interior of the Sun rotates significantly faster than its visible surface. Pursuit of this new area of investigation, which is coming to be known as "solar seismology," may eventually require a dedicated spacecraft with equipment capable of determining the amplitude and spatial structure of the oscillations. The need for nearly continuous data acquisition over a long period of time could be met by a spacecraft dedicated in whole or in part to the study of the Sun's internal dynamics.

Some of the above topics concerning the solar interior are also touched upon by W. H. Press in Chapter 4, dealing with Hydrodynamic and Hydromagnetic Phenomena in the Deep Solar Interior. Press stresses that the conventional view, that hydrodynamic and hydromagnetic effects are unimportant in the "deep" solar interior (below the region where convection is expected), may need modification. Observational data leading one to this opinion includes a possible light-element depletion, the apparent neutrino discrepancy, tentative indications of a rapidly rotating core, and the 160-minute oscillations. One mechanism that would lead to flows in the deep interior is deep convective overshoot below the convection zone. Another mechanism, which would operate in the solar core itself, is nucleothermal destabilization of g-modes, that is, the spontaneous excitation, by a thermodynamic mechanism, of waves that are more closely related to water waves than to sound waves. It is clear that current solar observational data provide a strong challenge to the long-held view that the interior of a star can be divided into a convection zone and a radiative zone free from radial motion. A more detailed understanding of internal flows in the Sun, and the mechanisms that drive them, would clearly have great significance for our understanding of stellar structure in general.

We referred, early in this summary, to the pressing need to improve our understanding of convection in the Sun. This is critical for understanding the observational data referred to in the preceding paragraph. It is also critical for understanding the solar dynamo, a topic discussed by P. A. Gilman in Chapter 5, The Solar Dynamo: Observations and Theories of Solar Convection, Global Circulation, and Magnetic Fields. It is widely accepted that the magnetic field visible at the Sun's surface is due to dynamo action in which the interplay of differential rotation, convection, and magnetic field leads to the enhancement of a weak field. A number of models of dynamo action have been developed in recent years; in most of these, turbulence is regarded as a small-scale random process, the effects of which may be described by a suitable averaging procedure. A typical dynamo model may show that a certain combination of differential rotation and turbulence will lead to the enhancement of a weak magnetic field, and nonlinear calculations may yield typical forms for the time evolution of the magnetic field in that model.

Until recently, the key test for a dynamo model has been comparison with the Maunder "butterfly diagram" representing the time variation of sunspot activity in latitude during the course of a solar cycle. Quite recently, important additional information concerning the sunspot cycle has been obtained by Howard and LaBonte. They find evidence for a "torsional oscillation" propagating in 22 years from the poles to the equator, the velocity amplitude of the oscillation being only 3 m sec^{-1}! This wavelike motion is closely related to the magnetic sunspot cycle and constitutes an additional fact that a successful dynamo theory must explain. An important question concerning the internal structure of the Sun is the possible existence of high internal rotation and strong magnetic fields. These questions, and their significance for solar physics and astrophysics, are discussed by R.

Ulrich in Chapter 6 on Solar Internal Stresses--Rotation and Magnetic Fields. Knowledge of the internal rotation and internal magnetic field is important for questions of cosmogony, since the initial rotation rate of the Sun must be at least as rapid as the present-day rotation rate of the core, and a magnetic field in the core must be a relic of the magnetic field in the primeval nebula.

Another reason for current interest in the internal stresses of the Sun is that rapid internal rotation should lead to circulation that would mix different layers of the Sun, tending to homogenize the element abundances. This process is important for our understanding of the observed abundance of light elements--such as lithium--on the Sun's surface. Furthermore, variation of the rotation rate with radius plays an important part in dynamo theory, discussed by Gilman, and may also have some importance in theoretical estimates of the neutrino production rate, discussed by Parker.

In recent years, a variety of techniques have evolved in an attempt to obtain information about the internal stresses of the Sun. Dicke and his collaborators, and more recently Hill and his collaborators, have made accurate ground-based measurements of the figure of the Sun, with the goal of measuring the solar oblateness. There is as yet no agreement on the observational results, and it is important that further observations be made, either from the ground or from space. As far as tests of general relativity are concerned, the crucial quantity to be determined is the gravitational quadrupole moment, which could perhaps be inferred from an accurate oblateness measurement but can be determined more precisely and unambiguously by study of the orbit of a spacecraft flying close to the Sun.

Ulrich and also Brown, Mihalas, and Rhodes, stress that accurate measurements of global oscillations of the Sun--such as could be made from space--hold great promise for study of the Sun's internal rotation and may possibly yield information about the Sun's internal magnetic field if this field is sufficiently strong.

We see, from the preceding discussion, that solar physicists are now concerned with, and seeking ways to determine, many aspects of the internal structure of the Sun: its rotation, magnetic field, convection, and oscillations, for example. Further advance in our understanding will depend critically on new observational data, such as a determination of the internal rotation rate as a function of radius and latitude. As Gilman points out, however, there is a critical need for information concerning the interaction between velocity fields and magnetic fields on very small spatial scales, smaller than that of the basic convection element near the photosphere, which is a "granule." To quote Gilman, "The necessary spatial resolution can only be obtained from a space platform such as the Shuttle, using the Solar Optical Telescope."

11. THE SOLAR ATMOSPHERE

The atmosphere of the Sun may be observed over a wide range of the electromagnetic spectrum ranging from radio to gamma-ray frequencies, sometimes with spatial resolution better than 1 arc sec, and with a variety of spectroscopic techniques that yield information on the line-of-sight velocity field and the line-of-sight magnetic field. The problem of inferring the structure of the atmosphere from observed radiation is discussed by R. G. Athay in Chapter 8 on Radiation Output. Direct inference of atmospheric structure from radiation output is not possible; the procedure must be based on models of the atmosphere or of components of the atmosphere. A detailed discussion of the complexities of Chromospheric Fine Structure is presented by Athay in Chapter 9. A phenomenological review of our knowledge of the upper atmosphere is presented in Chapter 10, Structure, Dynamics, and Heating of the Solar Atmosphere, written by F. Q. Orrall and G. W. Pneuman. A theoretical discussion of Physical Processes in the Solar Corona is presented in Chapter 11, prepared by T. Holzer, B. C. Low, and R. Rosner.

From these four chapters, it is clear that much has been learned in recent years about the Sun's atmosphere, yet fundamental questions remain unanswered. A few years ago, there was widespread belief that the corona is heated by a flux of acoustic waves generated by convective motion at the photosphere. However, spectroscopic observations made by means of the OSO-8 spacecraft indicate that the needed acoustic-wave flux is not present in the upper chromosphere. We learned from x-ray observations made by telescopes on Skylab that, at least in active regions, the structure of the solar corona is dominated by looplike structures that may be attributed to a magnetic field. It is therefore considered possible, and perhaps likely, that coronal heating in these regions is caused by the dissipation of magnetic energy.

Although such theories appear promising for active regions, it is not clear that coronal heating in coronal holes (which have predominantly open magnetic structure) can be attributed to the dissipation of magnetic energy. Although it appears likely that photospheric motions can slowly twist closed magnetic-flux tubes in active regions, to build up magnetic free energy in the form of field-aligned currents that can then dissipate and so heat the corona, photospheric motions cannot lead to an accumulation of free energy in the open magnetic-field configurations of coronal holes. They can produce outward-propagating torsional Alfvén waves, but these travel through the inner and middle corona without contributing significantly to coronal heating.

The challenge to our understanding of the solar atmosphere is, however, much greater than simply understanding the mechanism for coronal heating. One of the most important areas of research concerns the origin of the solar wind. According to early theoretical ideas, the solar wind is a direct consequence of the high temperature of the corona. Although it is clear that the corona can generate a wind, without any other mechanism being involved, this simple theory does not lead to a model that explains either the parameters characterizing the steady state of the solar wind or the great variability of these parameters. Hence current theoretical research involves the investigation of possible nonthermal processes that lead to the injection of additional energy and momentum into the solar wind, and there is a manifest need for observational evidence related to these questions, such as could be obtained by means of a solar-corona diagnostics mission.

The atmosphere involves a wide range of structures and dynamical phenomena including sunspots, fibrils, prominences, spicules, and "bright points," to mention only a few, all of which need to be explained if we are to say that we understand the solar atmosphere. Improved understanding depends crucially on the acquisition of improved diagnostic data with high spectral and spatial resolution, especially in the UV part of the spectrum. Holzer, Low, and Rosner also point out the need for more detailed magnetohydrodynamic (MHD) models of solar phenomena and stress that it is unlikely that these models can be constructed using analytical techniques alone. The current trend is toward the development of time-dependent, multidimensional MHD models with a level of complexity similar to that of codes being developed as part of the controlled thermonuclear reactor (CTR) program.

Recent discoveries have not been limited to the upper chromosphere and corona. Much has been learned also about the photosphere and low chromosphere. One of the most important discoveries has been the determination that much of the magnetic flux threading the photosphere is confined in small flux tubes, with diameters of order of 400 km, in which the field strength is between 1000 and 2000 G. These structures may well be the basic building blocks of magnetic-field structures in the Sun. If so, our models of the coronal magnetic field should consist of a number of discrete flux tubes rather than a distributed field configuration. The significance of this and related problems is emphasized by Athay in his chapter on Chromospheric Fine Structure. Observations of the required resolution will be possible only with the advent of the Solar Optical Telescope. Stereoscopic observations would be invaluable in resolving the three-dimensional structure of the atmosphere.

As we have noted above, study of the Sun's atmosphere does not end with the corona: the atmosphere extends outward into the solar wind, and the structure of the solar wind depends critically on the structure of the magnetic field and also on various nonthermal processes that may lead to the exchange of energy and momentum between various layers of the Sun's atmosphere and the solar wind. Thus, the upper regions of the solar atmosphere and the solar wind must be viewed as a tightly coupled system, and this close coupling emphasizes the importance of obtaining concomitant data, for instance by the joint operation of a solar-corona diagnostics mission and spacecraft that are part of the OPEN program. Looking even further into the future, we could obtain the necessary complementary information at high resolution from an advanced solar observatory equipped with several high-resolution instruments that operate at different wavelengths.

Solar activity, which is concerned with the development of active regions, pores, sunspots, and prominences, for example, may be viewed as the study of the active role of magnetic fields in the Sun's atmosphere. The most complex manifestation of this process is the flare that produces sudden bursts of energetic electromagnetic radiation, radio waves, high-energy particles, and plasma. It is believed that the energy released during a flare is associated with stresses (currents) in the coronal magnetic field, which have built up comparatively slowly as a result of changes and motions of the photospheric magnetic field. The sudden release of the energy stored in the coronal magnetic field is attributed to some form of plasma instability. These concepts are discussed in Chapter 12, Magnetic Energy Storage and Conversion in the Solar Atmosphere, by J. Boris, J. Mariska, and D. Spicer.

From an astrophysical point of view, one of the most important properties of a flare is the acceleration of particles to high energy--in the case of a solar flare, sometimes as high as 10 GeV. Our present understanding of the complex problem of acceleration in solar flares is reviewed by M. Forman, R. Ramaty, and E. Zweibel in Chapter 13, Acceleration and Propagation of Solar Flare Energetic Particles. Study of data concerning radio waves, x rays, gamma rays, and particles emitted from the Sun suggests that there are at least two different acceleration mechanisms at work in a solar flare. Three possible mechanisms discussed by the authors are stochastic acceleration, shock acceleration, and "direct" acceleration due to a low-frequency electric field parallel to the magnetic field. The energetic particles observed in interplanetary space are probably accelerated in the corona by shocks or by turbulence produced by shocks. The prompt acceleration of nuclei and relativistic electrons, as manifested by gamma-ray lines and continuum radiation, may be due to electric fields associated with current interuption or reconnection in closed-magnetic-field regions or to shock or stochastic acceleration in these regions. Clarification of these possibilities requires coordinated high-resolution observations at a variety of wavelengths--especially hard x rays--and in situ measurement of particle fluxes from the Sun. There is a need for observations by detectors of improved sensitivity and improved elemental and isotopic resolving power, such as would be provided by experiments on the OPEN spacecraft.

The detection of gamma-ray lines by spectrometers on the OSO-7, HEAO-1, and HEAO-3 spacecraft, and of gamma-ray lines and high-energy neutrons by the SMM spacecraft, has provided important new information concerning the acceleration of high-energy particles during flares. This topic is discussed in detail by R. R aty in Chapter 14, Nuclear Processes in Solar Fl.res. As Ramaty points out, "Gamma-ray lines are the most direct probe of nuclear processes in the solar atmosphere." One of the remarkable results to come from these observations is that protons and nuclei can be accelerated to energies of tens or even hundreds of MeV in only a few seconds. Solar gamma-ray astronomy has made a dramatic beginning. Future observation of solar gamma-ray lines with improved sensitivity and spectral resolution will provide unique information on particle acceleration during solar flares, particularly such questions as the timing of the acceleration, the beaming of the energetic particles, the temperature of the energetic-particle interaction site, and the compositions of the ambient medium and of the energetic particles. The continued operation of the gamma-ray spectrometer on SMM and the inclusion of gamma-ray detectors on future solar missions are crucial for these observations.

Radio observations provide a quite different channel for observing nonthermal processes occurring in the Sun's atmosphere, especially at the time of solar flares. A selective review of this extensive topic is given by M. Goldman and D. F. Smith in Chapter 15, Solar Radio Emission. Radio emission is due to electrons, but it appears that a variety of mechanisms are at work, including gyrosynchrotron radiation and radiation from plasma oscillations. In addition to observations obtained by dedicated solar observatories, important data have been obtained from the Very Large Array, which provides extremely high spatial resolution, and from low-frequency radio receivers on spacecraft such as those of the IMP series. Spacecraft penetrating into the solar wind, such as ISEE-C, are able to probe the region in which radio waves of very low frequency are believed to be generated. Such observations give direct insight into the way in which waves and oscillations are generated in a plasma by an electron stream and the nonlinear processes that eventually lead to radio emission.

As explained by Goldman and Smith, these observations have confirmed certain concepts but challenged others. These observations demonstrate that it is indeed possible to make in situ measurements of certain plasma processes of astrophysical significance.

12. THE SUN IN ITS ASTROPHYSICAL CONTEXT

Although much of the material discussed in earlier chapters of the report is applicable to a wide range of stars, and occasionally to nonstellar objects as well, it is instructive to focus on the relationship between the Sun and other main-sequence stars. This is the theme of Chapters 16 through 19 of the report.

Information concerning the The Formation of the Sun and Its Planets is reviewed by W. M. Kaula in Chapter 16. There is reason to believe that two supernova events preceded the formation of the solar system, one 200 million years before formation and the other only 2 million years before. The latter may possibly have influenced the collapse of the primeval gas cloud. Studies of remanent magnetism and inert gases in meteorites indicate that the early Sun was considerably more active than the present Sun. As we shall see later, this appears to be a typical trend for single main-sequence stars.

It has been found that, for binaries with periods of less than 100 years, the frequency with which a primary is found to have a secondary companion increases as the one-third power of the ratio of the mass of the primary to the mass of the secondary. If this law is assumed to apply to smaller primary masses than the range for which it was established, one infers that almost all stars of mass less than about 1.5 solar masses have companions, the smallest companions being planets. Observation of Barnard's star gives suggestive, but not conclusive, evidence that there are planets in orbit around that star. Hence, from a strictly observational viewpoint, we still do not know whether the Sun is unusual in having planets.

Since, in developing models of the Sun, one of the critical parameters is its assumed age, it is perhaps appropriate to reconsider the usual assumption that the age of the Sun can be inferred from the age of meteorites. In order to resolve this question, we need even more-detailed models of the evolution of the primeval nebula into a central object and a surrounding disk, with the central object evolving into a main-sequence star, and the disk condensing first into planetesimals and then into planets. Such studies may help to resolve some current problems, such as the fact that chondritic meteorites indicate higher nebula temperatures (of the order of 1500 K) than are provided by present models. Some of the content of Chapter 17 by M. J. Newman, The Solar Neutrino Problem--Gadfly for Solar Evolution Theory, has been discussed in conjunction with chapters dealing with the solar interior. However, Newman also points out a number of questions concerning the evolution of the Sun that have been brought to the attention of the astrophysics community by the neutrino problem. It has been suggested that the initial Sun may have been nonuniform in the sense that the composition was a function of radius, that a strong primordial magnetic field is locked in the core, and that the core rotates much more rapidly than the surface. Information about the solar interior to be obtained by solar seismology discussed earlier in this summary, may clarify these possibilities. Other relevant data may be obtained by gravitational tests involving a spacecraft or by accurate measurements of the figure of the Sun.

Chapter 18 by J. P. Cassinelli and K. B. MacGregor, Stellar Chromospheres, Coronae, and Winds, and Chapter 19 by R. W. Noyes, Solar and Stellar Magnetic Activity, both deal with chromospheric and coronal radiation from the Sun and similar stars and with related topics. As Cassinelli and MacGregor remark, "The discovery of chromospheres, coronae, and winds associated with stars other than the Sun affords a unique opportunity for the fruitful exchange of ideas between solar and stellar physicists. In particular, the observation and interpretation of solar-type phenomena in stars of different spectral types, luminosity classes, and ages should significantly increase our understanding of the Sun as a star."

Since the solar corona is strongly influenced by--and may even owe its existence to--the solar magnetic field, and since the chromosphere also is strongly affected by the magnetic field, study of these regions is tightly coupled to the study of magnetic activity in general and the dynamo process in particular. White-light observations of stars give evidence for the existence of spots, rotation, and even differential rotation. The existence of spots is closely coupled to chromospheric activity that may be conveniently monitored by means of Ca II emission. Measured in this way, chromospheric activity in stars is found to be related to star spots in much the same way as it is on the Sun. Surveys of chromospheric activity in main-sequence stars have given valuable insight into the way in which dynamo activity depends on stellar parameters. For stars of a given spectral type, older stars show cyclic behavior similar to the solar cycle, whereas younger stars show a stochastic variation in activity. There is a clear gap between these two regimes. It appears, therefore, that there are at least two distinct regimes of dynamo activity and that a star may be comparatively quiet for a short time after leaving the chaotic regime and before entering the cyclic regime. Such data, derived from large numbers of stars, provide stringent additional tests for dynamo models, above and beyond tests derived from solar data alone.

Similarly, analysis of chromospheric and coronal emission from other stars provides an additional test of theories of chromospheric and coronal heating developed originally for the Sun. We find, for instance, that data on stellar coronas disagree with the implications of acoustic heating theory, as is the case for the solar corona. In attempting to understand strong patterns such as the Wilson-Bappu effect, relating the width of Ca II line-emission cores with luminosity, astrophysicists may build upon our understanding of the solar chromosphere but must also estimate the way in which atmospheric parameters vary with the basic stellar parameters of effective temperature and surface gravity.

Consideration of the problems posed by stellar observations calls for additional information, some of which can best be obtained by further observation of the Sun. For instance, spatially resolved observations of the magnetic and velocity fields on the Sun, such as can best be obtained from the Solar Optical Telescope, are required to tighten constraints on the dynamo mechanism and on the mechanisms involved in small-scale processes such as sunspot formation, flares, and spicules. We also need further information on the latitude, longitude, and solar-cycle-phase dependence of ephemeral active regions that can be observed as coronal bright points. This information could be provided by a solar-corona diagnostics mission.

Supplementary diagnostics information on coronal structure can be obtained by high-resolution observations of the pinhole type. In order to obtain further information about the way in which a wind exerts a braking torque on a star, such as the Sun, we need out-of-the-ecliptic observations of the solar wind.

Similarly, our understanding of the Sun could be advanced by increasing our knowledge of stellar atmospheres and stellar activity. It is desirable to have more-detailed observations of the chromospheric and coronal radiation to learn more about the way in which the dynamo mechanism varies with basic stellar parameters and to provide further checks of theories of chromospheric and coronal heating. Some of these observations can be made from the ground, but UV and x-ray observations must be made from space and may in fact warrant Shuttle facility instrumentation or dedicated Explorer-class spacecraft.

13. SOLAR-TERRESTRIAL RELATIONS

One of the most important reasons for studying the Sun in great detail is to improve our understanding of the various ways in which the Sun affects our terrestrial environment. As time goes by, we are improving our understanding of certain of the well-established effects, such as geomagnetic storms, but we are also obtaining evidence pointing to new and unsuspected effects, possibly even including solar influences on climate and weather.

The very complex manner in which the Sun's electromagnetic radiation influences the Earth's atmosphere, and all life forms on Earth, is outlined by R. Dickinson in Chapter 20, Effects of Solar Electromagnetic Radiation on the Terrestrial Environment. These effects involve a combination of physical, chemical, and biological processes. The sensitivity of the Earth's climate to variation of insolation has recently been underscored by the demonstration that historical major climatic fluctuations may be attributed to variations in the Earth's orbital parameters. In particular, variations of insolation due to orbital effects are believed to have been a contributing cause of the last ice age that peaked 20,000 years ago, as well as earlier ice ages over the last million years.

Recognition of the sensitivity of our climate to fluctuations in solar radiation received on Earth clearly makes it important to understand the stability--or lack of stability--of the total radiative energy input from the Sun, heretofore referred to as the solar constant. The intrinsic fluctuations are extraordinarily difficult to measure from the Earth's surface. Measurements have been made over a period of over 2 years, however, by the active cavity radiometer on the SMM spacecraft. This instrument has a precision of 100 ppm and can detect changes much smaller than this value. Measurements with this instrument have shown that the Sun's luminosity is far from constant; a variation of 1000 ppm may be measured in one solar rotation.

It will be important to try to determine what changes, if any, in the Earth's atmosphere may be correlated with these changes in the Sun's luminosity. The atmospheric aspects of this problem fall within the purview of the Upper Atmosphere Research Satellite program. Solar physicists, for their part, are trying to understand the origin of these fluctuations. There is certainly a strong component that may be attributed to sunspots, but there are other effects that must be pinned down. The very fact that sunspots can cause a diminution of the total radiative output from the Sun came as a surprise to many solar physicists, who believed that the "missing flux" from a sunspot would appear elsewhere on the Sun's surface with negligible time delay. It now seems that substantial amounts of energy are being stored in the outer layers of the Sun, and further study of the influence of sunspots and other features on the Sun's luminosity may yield valuable insight into the structure of the Sun's convection zone, the transport of energy through that zone, and perhaps into the nature of stellar convection itself.

In addition to the effects on the Earth's atmosphere of variations of the total radiation from the Sun, we know that certain layers of the Earth's atmosphere--such as the ionosphere--are very sensitive to variations in solar ionizing radiation, including UV and x-ray. Changes in the ionosphere are important for a number of reasons, including the effect of such changes on radio propagation, as will be discussed later.

Changes in the solar wind itself, and changes in the magnetic field that permeates the solar wind, can both have important terrestrial effects, as discussed by N. Crooker and G. Siscoe in Chapter 21 dealing with The Effects of the Solar Wind on the Terrestrial Environment. For instance, when the interplanetary magnetic field that sweeps past the Earth has a southward component for an hour or longer, there are auroral displays and there may even be disruptions in power distribution systems and in radio and cable communication systems also. It is somewhat surprising that the impact of the expanding corona can be so pronounced, since its energy flux is 6 to 7 orders of magnitude smaller than the energy flux radiated by the Sun and the solar wind hardly penetrates the magnetosphere: only about 0.1% of the solar-wind mass flux incident on the magnetopause manages to cross it.

It is clear that subtle effects take place in the Earth's magnetic-field structure, caused by the interplay of the solar wind with the magnetosphere, which is the primary concern of the OPEN program. This interaction is sensitive to the direction of the magnetic field permeating the solar wind. A number of characteristic forms of interaction have been identified. For instance, it is known that high-velocity streams have predictable effects. Some of these streams, often associated with coronal holes, are long lived so that they recur with a period of approximately 27 days owing to the Sun's rotation. Other streams, such as those produced by coronal transients and other flare-related processes, are nonrecurrent. These nonrecurrent streams tend to have higher velocities and so give rise to shock waves that have important geomagnetic effects.

Even in the absence of solar activity, the Earth's magnetosphere is not static. Interaction between the magnetosphere and the solar wind at the magnetopause gives rise to convection of the magnetospheric plasma. This in turn gives rise to field-aligned or "Birkeland" currents that transfer energy from the magnetopause, where it is derived from the solar wind, to the ionospheric layers in the auroral regions. These currents play a key role in ionospheric electrojets, auroras, and magnetic substorms.

During times of magnetic activity, high-energy electrons from the outer magnetosphere may penetrate to the middle atmosphere, where their presence leads to a depletion in the stratospheric ozone. Because ozone in the middle atmosphere affects the radiation reaching the lower atmosphere, changes in the stratospheric ozone abundance could conceivably influence the Earth's weather.

There have been claims for over 100 years that some component of the Earth's weather fluctuations may be attributed to solar influences. For instance, there is some statistical support for the proposition that droughts in the high plains of the United States tend to occur at every other sunspot minimum. On a shorter time scale, there is suggestive evidence that a correlation exists between an atmospheric vorticity index and the passage of sector boundaries in the solar wind, where the predominantly radial component of magnetic field changes sign. There is need for an relation and a vigorous search for physical mechanisms that might explain such effects.

In addition to the steady output of charged particles that make up the solar wind and sudden changes in that flow, such as coronal transients and high-speed streams, the Sun also emits occasional streams of high-energy ions and electrons. These processes are reviewed by G. Reid in Chapter 22, Solar Energetic Particles and Their Effects on the Terrestrial Environment. The influence of these particles on the terrestrial environment depends critically on their access to the Earth's atmosphere, which is determined by the structure of the Earth's magnetosphere. Particles may most easily reach the polar caps, where the magnetic field couples into the Earth's geomagnetic tail, or even out into interplanetary space. Hence, solar "particle events" typically cause enhanced ionization in the polar-cap regions of the ionosphere. This gives rise not only to greatly increased absorption of radio waves, which may amount to a radio blackout, but also to a change in the phase of transmitted waves, which can have important adverse influences on radio navigation systems. The flux of solar particles directly into the polar-cap regions also gives risev to a faint, diffuse aurora over the entire polar cap, called a polar-glow aurora. This is one of the few observable effects that may be attributed directly to solar particles.

The influx of high-energy particles into the Earth's atmosphere also has important chemical consequences. For instance, energetic particles can dissociate molecules, giving rise to an increase in NO concentration, leading in turn to NO_x compounds. Furthermore, such chemical changes have an important influence on the ozone abundance, so that solar particle events can lead to a reduction in the stratospheric ozone content. As Reid remarks, "Solar-particle events clearly have the potential for modifying the chemical composition of the middle atmosphere."

The terrestrial effects of solar-particle events vary greatly from case to case. For instance, the February 1956 event increased the ground-level neutron flux by a factor of 90 in some regions and added 10 percent of an entire solar cycle's supply of ^{14}C. The events of August 1972 caused a substantial and long-lasting prehistoric times, there may well have been much larger events. One must also remember that the Earth's geomagnetic field has gone through reversals. If the Earth's magnetic field dropped to a very low value during a reversal, the Earth would not have been shielded from charged particles as it is now. There is indeed some evidence for correlation of the extinction of marine micro-organisms with polarity reversals, and some evidence for correlation of polarity reversals with changes in the Earth's climate.

As mentioned earlier, understanding of any apparent statistical correlation between solar activity and solar-sector structure, on the one hand, and the Earth's climate and weather, on the other hand, requires that one identify a trigger mechanism by which a phenomenon with little energy content can influence the Earth's global circulation pattern, a system with comparatively high energy content. Proposed trigger mechanisms are either electrical, radiative, or dynamical.

Of these possibilities, one of the most interesting is that the global electric field plays a key role. It is known that the electrical conductivity of the Earth's upper atmosphere is strongly influenced by the galactic cosmic-ray flux, and we know that the cosmic-ray flux is strongly influenced by the interplanetary magnetic field. Unfortunately, as Reid points out, "Our understanding of the global electric field is fairly rudimentary." If the statistical case for a correlation between a nonradiative solar output and the Earth's weather becomes convincing, and if the search for a physical mechanism zeros in on the global electric field, it will then become most important to find some mechanism for obtaining global synoptic data of the atmospheric electric field. NASA is currently supporting a tethered balloon program designed to address this problem, but the need for acquiring global data should stimulate a search for some method of measuring electric fields from space. No proposals for such measurements have yet been advanced.

It will be noted that the study of solar-terrestrial relations is important not only for practical reasons; the recognition of such effects also poses searching questions concerning the Sun itself and the complicated environment of the Earth.

In conclusion, we would point out that the material contained in this report and the extensive studies on which it is based, present the clear picture that solar physics is now in an exciting state in which observations have sometimes confirmed established concepts, sometimes called for their modification, and sometimes called for the development of new models and theories. Furthermore, solar physics is enriched by the fact that it may be viewed as a test bed of physics in the context of stellar astrophysics or as the point of origin of solar-terrestrial relations. Given continued support for space and ground-based observations, data analysis and theory, continued research on the physics of the Sun should pay handsome dividends.

14. RECOMMENDATIONS

The following recommendations have been framed by the Advocacy Committee on the basis of advice provided by many members of the solar-physics community and extended discussions with the Advocacy Policy Panel.

BASIS FOR RECOMMENDATIONS

A. Since the Sun is the source of energy for many of the natural phenomena in the solar-system environment, including those responsible for solar-terrestrial relations, a detailed understanding of all forms of the Sun's variable energy output is essential for a thorough understanding of these phenomena.

B. The Sun is the most thoroughly studied and best understood astrophysical system. Because of the detailed information available for the Sun, knowledge gained from research in solar physics provides a basis for understanding not only other stars (of all spectral types and luminosity classes) but also many other astrophysical systems in which one can identify physical processes similar to those operating in the Sun.

C. Solar physics has a symbiotic relationship with many branches of the physical sciences including atomic and nuclear physics, hydrodynamics, and the physics of magnetized plasmas. Since solar physics requires the application of physical theories to conditions that cannot be reproduced in the laboratory, our progress toward understanding these physical processes can proceed along distinct but complementary paths in solar and laboratory physics.

D. A thorough understanding of the physical processes involved in solar phenomena is essential both for a complete understanding of solar-terrestrial relations and for the transfer of knowledge about the Sun to other astrophysical systems.

E. The past decade has produced a number of important advances in our understanding of solar physics. These advances in turn pose new fundamental questions that represent challenges to our current understanding of the Sun. Beginning with the solar interior and working outward, a representative list of these advances includes the following:

1. Analysis of the contradiction between observational data and theoretical predictions concerning the Sun's neutrino emission;
2. Development and early application of an observational technique, similar to that used in terrestrial seismology, for probing the Sun's interior;
3. Acquisition and analysis of qualitatively new solar data and stellar data relevant to the dynamo process and the development of greatly improved theoretical models of this process;
4. Acquisition of an extended sequence of highly accurate measurements of the temporal variation of the solar irradiance (previously known as the solar constant);
5. Realization that magnetic fields play a crucial role in the structure and heating of the Sun's atmosphere and that understanding of energy transport processes in the solar atmosphere must be based on the comprehensive analysis of chromospheric and coronal fine structure;
6. Acquisition of gamma-ray and hard x-ray data that provide qualitatively new information concerning particle acceleration in solar flares; and
7. Continuing clarification of the relationship between coronal and solar-wind structures and of the implications of this relationship for both coronal heating and the origin of the solar wind.

F. The long-term health of solar physics requires a continuing flow of new graduate students who have sound training in the various fields of physics that are essential for the understanding of solar processes. The ties between university groups active in solar physics and physics departments need to be strengthened.

G. Continued improvement in our understanding of the physics of the Sun will require a solar-physics program of sustained vitality. The development of this program must be based on the close relationship between solar physics and other disciplines indicated in A-D above and take account of the need for increased university involvem… .ndicated in F. These conclusions lead us to make the following recommendations.

RECOMMENDATIONS

A. We recommend a vigorous NASA solar research program that emphasizes the investigation of physical processes, especially those that bear on the Sun's influence on the terrestrial environment and the relationship between the Sun and other astronomical objects. This program should be planned in such a way as to promote strong interaction between research workers in solar physics, solar-terrestrial physics, stellar physics and other areas of astrophysics and relevant areas of physics.

B. We recommend that NASA provide increased flight opportunities, supported by instrument development, data analysis, theoretical research, and appropriate ground-based operations, directed toward the solution of specific outstanding problems of solar physics, including the following:

1. The structure and dynamical processes of the Sun's radiative interior and convective envelope;
2. The mechanisms responsible for the generation and cyclic variation of the Sun's magnetic field;
3. The nature and cause of solar luminosity variations in all regions of the electromagnetic spectrum;
4. The origin, structure and dynamics of small-scale magnetic features;
5. The role of small-scale magnetic fields in the dynamic and thermodynamic properties of the chromosphere and corona;
6. The transfer of energy and momentum from the corona to the solar wind and the effect of this transfer on the corona; and
7. The electrodynamic and magnetohydrodynamic processes responsible for particle acceleration in solar flares.

C. We recommend that studies directed toward the above goals be supported by accelerated development of the requisite advanced instruments, which, after flight testing on suborbital vehicles followed by short-term Shuttle/Spacelab missions, will be deployed on free fliers and incorporated into major space observatories.

D. We recommend that NASA strengthen the role of solar physics in the academic community by supporting the evolution of a small number of strong physics-based university research groups that include experimental, data-analysis, and theoretical components.

APPENDIX

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The Sun and Astrophysics

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Chapter 17. The Solar Neutrino Problem: Gadfly for Solar Evolution Theory (M. Newman)
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